20th International Conference
ENGINEERING MECHANICS 2014
Svratka, Czech Republic, 12 – 15 May 2014

ATOMISER WITH EXCITATION BY A FLUIDIC OSCILLATOR

V. Tesař, J. Hykl*

Abstract: *Paper summarises results obtained in preliminary feasibility study of a novel pneumatic atomiser for generation o fine droplet spray. The new feature is pulsating the air supply by means of a no-moving-part fluidic oscillator. Tests involved recording by high-speed camera and optical measurements of the droplet size by laser light scattering and suggested a promising future potential necessitating, however, further development and optimisation.*

Keywords: Atomiser, Droplet spray, Fluidic oscillator.

1. Introduction

Atomisers are devices generating a spray of fine liquid droplets dispersed in a gas atmosphere. There is an obvious mutual correspondence with the reverse case of gas bubbles dispersed in a volume of liquid. For investigations of the bubbles in the period 2012-2013 the present first author received a research grant to study the possibility of obtaining smaller droplet size by the action of flow pulsation generated by a fluidic oscillator. Because of the above mentioned correspondence, a similar effect of small size droplets may be, in principle, obtained by an action pulsation also generated in a fluidic oscillator. To investigate this idea, a small part of the grant means were diverted at the end of the year 2013 to design an manufacture the new fluidic atomiser concept and perform simple tests with it. Because of the different aim of the main project, the testing was not extensive – it was only a feasibility study. Nevertheless the results may be described as promising and because no similar attempts were found discussed in literature, legal protection of the idea by a Czech Republic Patent was applied for, still in the examination stage. The present paper describes the accumulated results that, considering the limited extent of time and means spent, are quite interesting.

2. Known Standard Principles of Atomisers

The principles used nowadays for generating sprays of fine droplets may be listed as follows:

(a) Percolation through a small nozzle
(b) External mixing pneumatic
(c) Pneumatic effervescent (internal mixing)
(d) Centrifugal
(e) Ultrasonic
(f) Vapour condensation

Fig. 1: List of standard atomiser principles.

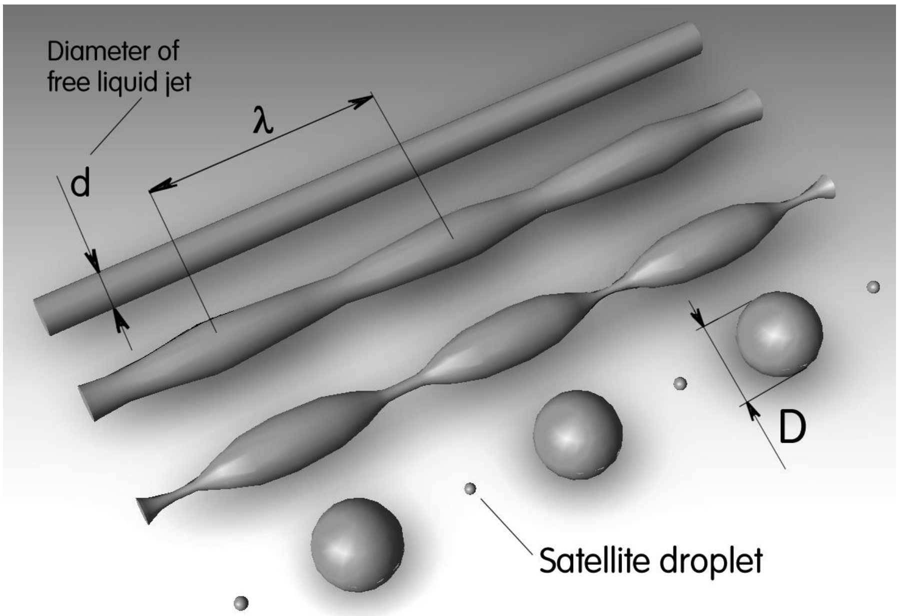
a) The simplest principle is the generally known fact that a liquid jet, accelerated into atmosphere inside a nozzle by acting pressure difference, disintegrates into a spray of drops. This breakup was first studied by Belgian scientist Plateau [1] already in 1873. He noted that the surface energy of the

* Prof. Ing. Václav Tesař, RNDr. Jiří Hykl PhD.: Institute of Thermomechanics v.v.v.i., Academy of Sciences of the Czech Republic, Dolejškova 5; 182 00, Prague; CZ, tesar@it.cas.cz

jet in the form of a circular cylinder is larger than that of spherical drops having the same volume. The jet tends to break into segments of equal lengths from which the drops are then formed by convolution driven by surface tension. Plateau evaluated the minimum resultant surface energy obtained when the jet segments are π-times longer than the jet diameter d. The transition by capillary pinching between the constant-diameter cylinder and the separate segments, as presented in Fig. 1, was later studied by Rayleigh [2, 3]. He considered a free shear-less jet issuing from a circular nozzle of diameter d and by taking into account only surface tension and inertial forces he found the most favoured growth of disturbances (waves) on the cylinder surface if their wave-length is $\lambda = 4.51\ d$. The size D of the drops, Fig. 2, is evaluated from the equality of the volumes:

$$4.51\ (\pi/4)\ d^2 = (\pi/6)\ D^3 \quad \ldots\ D = 1.89\ d \tag{1}$$

The theory was further extended by Weber in 1931 [4] who considered the influences neglected by Rayleigh. Having included into the analysis the resistance of surrounding air, he found this effect shortens the wavelength. For the case of zero relative velocity between air and liquid he found $\lambda = 4.44\ d$. Next important contribution was by Taylor (1962) [5], whose achievement was derivation of the theory for generation on the small excrescences on the surface that produce the "satellite" droplets (Fig. 2). These in are important in many applications, often causing troubles (for example, they must be removed in jet printing actuators since they would smear details of the printed pictures and letters [6]).



:

Fig. 2: Geometry of the shear-less liquid jet of diameter d breaking up by growth of surface waves into segments that finally convolute into drops of diameter D.

b) Weber's [4] theory has shown favourable effect – decrease of the droplet size – of the relative velocity between air and liquid. In the usual configuration of an atomiser using this effect, a fast annular air jet surrounds the central liquid jet. Already for the quite small value of the relative velocity 15 m/s the theory in [4] shows that λ becomes $2.8\ d$ and the drop diameter decreases to $D = 1.6\ d$. The effect, of course, is more pronounced for higher relative velocities. This is the reason behind the success of the pneumatic principle – despite the inconvenience caused by the need for a compressed air source. The advantage is the vast differences (practically three decimal orders of magnitude) in specific volumes v [m^3/kg] and consequently high differences in velocities between the liquid and the gas at the same driving pressure drop ΔP. In the first approximation (neglecting the internal losses inside the nozzle, which are usually not significant) the outflow velocities are

$$w = \sqrt{2 v \Delta P} \tag{2}$$

This difference leads to very small size D of the generated drops, a property used to advantage especially in liquid fuels combustion systems, in particular in gas turbines where availability of the compressed air is no problem.

Conditions of the droplet formation inside the atomiser are characterised by dimensionless Weber number

$$We = \frac{w^2 d}{2\sigma v} \quad (3)$$

- essentially a ratio of specific kinetic energy of the liquid flow $w^2/2$ and the specific surface energy. The quantity σ [N/m] is the surface tension. Another dimensionlessparameter useful in investigations of droplet formation is the Ohnesorge number

$$Oh = \frac{\nu}{\sqrt{\sigma v d}} \quad (4)$$

It characterises the relative influence of viscous forces (the quantity ν [m^2/s] is the kinematic viscosity) on the square root of the product of inertial and surface forces. Unfortunately neither We nor Oh fully characterise the conditions – there is also a strong dependence on Reynolds number [7].

c) A more complex character of the liquid / gas mixing is employed in the effervescent pneumatic principle – in other words, in atomisers with internal mixing of the gas and liquid. Usually this principle is used in a hybrid combination with the external mixing. As shown in the example presented in Fig. 3, a part of the supplied air flow is diverted into the liquid-filled cavities where it generates a two-phase mixture. The rest of the air is used in the external mixing.

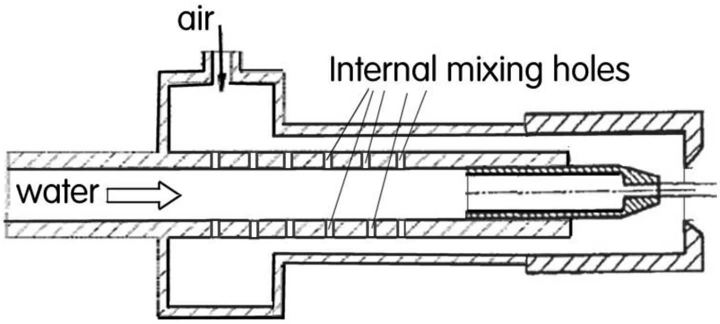


Fig. 3: As in this example of a traditional effervescent atomiser, the internal mixing is usually combined with external mixing . The primary internal mixing is a diverted by part of the air flow admitted through the internal holes into the water flow. External mixing then takes place doenstream between the central two-phase flow and surrounding annular high-speed air flow.

When the liquid/gas mixture passes through the exit nozzle, the instantaneous velocity varies in an alternating manner. Because of the larger specific volume of the gas and hence its stronger response to the acting pressure difference, the exit flow velocity varies between high value when there is the gas and the low value then the fluid is the liquid. This unsteadiness leads to generation of structures (elongated liquid ligaments) in the exit flow, from which the droplets are then formed by the Plateau-Reyleigh mechanism [7].

The atomiser with fluidic excitation discussed in this paper belongs into the pneumatic atomiser category and may be - perhaps with some extrapolation of the definition of the term - described as belonging to the effervescent principle (or, as shown below, may be quite easily adapted, by providing an internal mixing hole (or holes), as discussed below in (d). The new feature so far not discussed in literature is the periodic unsteadiness.

d) In the atomiser belonging into the centrifugal family the liquid is admitted on the surface of a spinning disk and left to leave the disk by the action of centrifugal force. The starting point in the mixing, still on the disk, waves are formed on the liquid surface like in the percolation case (a), due to the velocity difference between the moving liquid surface on the disk and the stationary outer gas. The waves tend to divide into segments and after leaving the disk edge the segments are convoluted into the spherical droplets. The droplets generated by these atomisers tend to be rather large and of widely differing diameters.

e) In atomisers of this category, the liquid gets into contact with an oscillating mechanical component – which may be directly the piezoelectric actuator, usually a small ceramic body with metal electrodes on its surfaces upon which the liquid is admitted. The acting mechanism is fragmentation of the liquid objects, beginning with waves formed on the free liquid surface. Their amplitudes grow until the peaks get pinched off and fly away is small droplets. Because of generally poor efficiency, this principle is used mainly in small-scale devices, like e.g. inhalators [7].

f) Energetically very demanding is the principle based upon evaporation of the liquid. The vapour is then led through a cooled chamber or cavity in which condensation of the vapour takes place. This principle is used in those (quite rare and special) situations where there is a strong demand for extremely small (perhaps micron-size) droplets in a small range of diameters.

3. The New Principle

The new idea – described in the Patent Application [8] – is essentially an extension of the pneumatic principle corresponding to (b) or (c) in the list of Fig. 1. Like in these two principles, the new atomiser is also supplied by compressed air and generates the small droplets by the shear stresses acting on the gas/liquid interface. The novel patented feature is the oscillation of the air flow at the atomizer inlet by the integrally in-built fluidic oscillator. This is in the very basic principle the same idea as was recently introduced according to [9] in the inverse configuration, to generate very small gas (air) microbubbles in liquid (water). The oscillation is applied on the air side. In both [8] and [9] the discussed oscillator was driven by extracting a small part of the energy from the supplied air.

The configuration, however, differs from that described in [9], where the oscillation was applied so as to slow down temporarily and then - in the next half of the period – to accelerate the supplied air flow. In the configuration discussed here [8] the action is different. Bothe the supplier water and air flow rates remain constant in magnitude, but the water jet is acted upon transversally, periodically varying its flow direction.

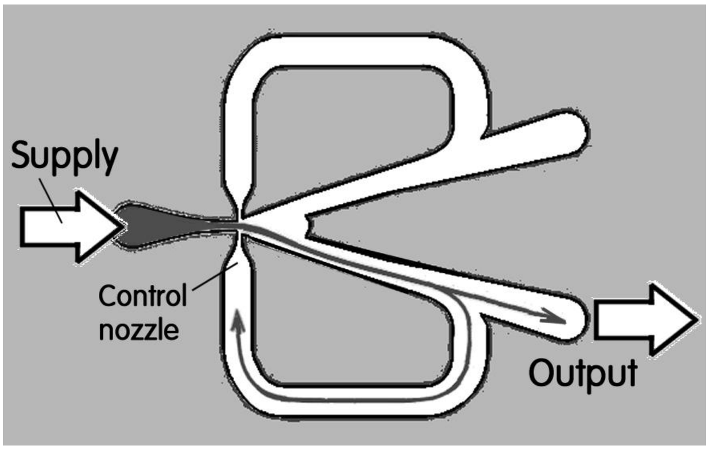


Fig. 4: A typical fluidic oscillator with alternating output flows issuing from the two output terminals. The basic part is the jet-deflection type fluidic diverter amplifier. It is converted into the oscillator by the addition of two loops carrying the feedback signals from the amplifier outputs into the control nozzles. The feedback is a negative one: its action decreases the cause that produced it.

The use of a fluidic oscillator is an important part of the patented configuration in [8]. The no-moving-part fluidic devices operate by using some special fluid-dynamic effects in constant-geometry cavities [10]. These effects are mostly based on some form of hydrodynamic instability: a small action applied in some sensitive location can cause a total change in the character of the whole flowfield. This disproportion between the small cause and its large consequences is the basis of the idea of fluidic amplification. An example of an amplifier shown in the central part of Fig. 4 — where it is a part of the oscillator to be discussed below. The amplifier is of the bistable jet-deflection flow diverter type. The working fluid is supplied into the main nozzle at left and by issuing from the supply nozzle generates a jet. Downstream from the supply nozzle is the interaction cavity with two symmetrically positioned attachment walls. The angle of these walls is so large that the flow cannot attach to both of them. By the Coanda effect mechanism it attaches to one of them. In Fig. 4 the arrows indicating the character of the air flow in the amplifier show the supply jet attached to the lower of the attachment walls. This wall guides the flow to the lower of the two output terminals. Essential for the operation of the amplifier is the very large sensitivity of the supply jet to even a weak flow signal issuing from the control nozzles. This control signal quite easily switches the flow from the bottom attachment wall to the upper one.

The oscillator needed for the operation of the discussed atomiser is obtained from the amplifier by addition of feedback loops. In Fig. 4 the feedback is provided by the two channels arranged in two loops. In each of them some flow is taken from the output and returned (fed back) into the control nozzle. There it switches the jet from the supply nozzle so that it flows into the upper output terminal. This, however, generates the negative feedback in the upper loop – which, together with the absence of the fluid flow in the bottom loop, switches the jet back. This places the oscillator into the starting position and the process may be then repeated.

Typical in this illustration – as well as in the other drawings Figs. 5, 6, 7 etc. – is the planar design. The device consists of three plates, all of constant thickness. The key component is the middle plate in which are made the cavities for the fluid flows. Typically the cavities are made by laser cutting. All plates are, also typically, of rectangular outer shape. The other two plates, top and bottom cover plates, are there to close the cavities and also to provide a mechanical support – for this reason the cover plates may be thicker.

Even though in Fig. 4 above is shown only a more or less schematic representation, intended only to provide an explanation of the feedback action, the geometry of the amplifier and amplifier in this picture actually closely corresponds to the first author's successful earlier oscillator designs. The jet performing the alternating switching motions is generated in the supply nozzle at the left-hand side of the illustration. In this nozzle the fluid flow is accelerated (note the small cross-section of the supply nozzle compared with the wider space in the interaction cavity located downstream from this nozzle). Once the jet passes through the interaction cavity, it is advisable to convert its kinetic energy back into the pressure energy. Otherwise too much energy of the fluid flow would be lost – since hydraulic losses, of course, are roughly proportional to the square of velocity. This return conversion is performed in the diffusers with diverging walls recognisable in Fig. 4. Note that a too rapid divergence would be dangerous, the flow may separate from the diffuser walls. An important feature worth being mentioned is the provision of a small internal positive feedback provided by the bi-cuspid shape of the nose of the splitter between the two diffusers. It produces an internal vortex inside the interaction cavity which – together with the Coanda-effect attachments – tends to keep the supply jet deflected. The oscillation has therefore not a character of sinusoidal variation of the flow in one of the output terminals but, instead, a switching between the two outlets with the flow/time dependence having a character of a train of rectangular flow pulses. Of course, this positive feedback is a weak one and is easily overcome by the negative feedback that produces the oscillation.

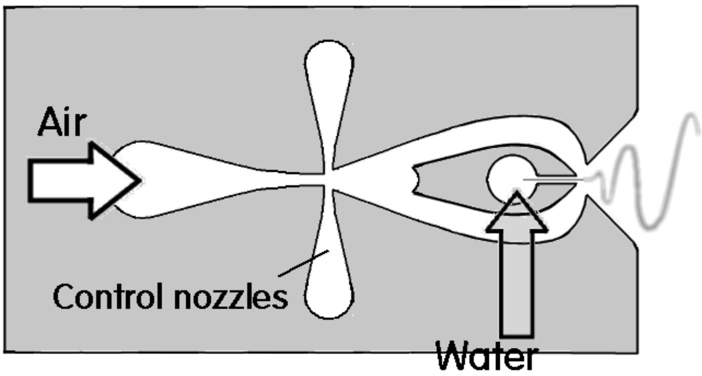


Fig. 5: The key details of the atomiser with fluidic excitation. The geometry was developed from earlier jet-deflection flow diverter oscillators, as shown in the previous Fig. 4. There are no feedback loop channels here, because there are several alternatives how to introduce the negative feedback.

The basic features of the discussed atomiser are presented in Fig. 5. It is a self-excited device – of course, if provided with some form of feedback not shown in this picture. It is obvious that in principle it retains the geometry and oscillation generation principle of the amplifier from Fig. 4. In particular, it is apparent in Fig. 5 that the geometry of the supply nozzle, control nozzles and the interaction cavity are actually identical to those in Fig. 4. The channels downstream from the interaction cavity are, however, different. The generated air flows should act on the water flow with considerable momentum and therefore there is no need of the diffuser effect (slowing down of the flow). Also, these channels are not straight but curved so that their downstream ends are near to one another. In this region the air output flows act in alternating manner on the jet of water. It should be noted that, based on previous experience with fluidic amplifiers, also this atomiser retained the week internal positive feedback action, made by the bi-cuspid nose of the splitter – between the two entrances into the two curved exit channels downstream from the interaction cavity.

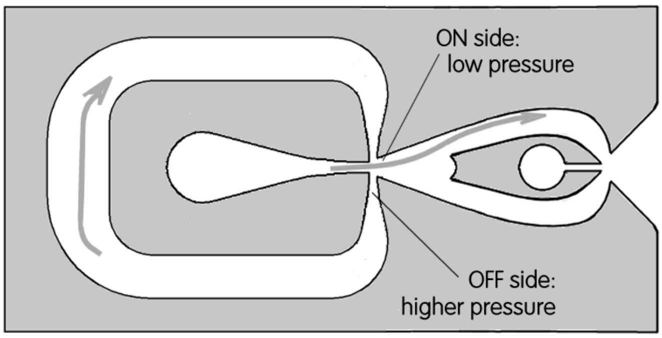


Fig. 6: Possible alternative version of the atomiser with feedback of the single-loop type (which, because of its simplicity, may have some advantages from the manufacturing point of view). The feedback loop connects the control nozzles. Flow in the loop is generated by the pressure difference between the ON and OFF sides. This principle of introducing the negative feedback was investigated in detail e.g. in ref. [11], where more detailed information on this kind of feedback may be found.

In the area between the curved channels is placed a small component – the water injection body. On its upstream side is the half-moon cutout between the two cusps. Noteworthy in the water injection body is its rather large round central hole. This serves for inflow of water – again from a direction perpendicular to the drawing plane and the narrow water-exit nozzle at the downstream end of this small water-injection body. The alternating exit flows impart sideways blows to the water jet issuing from this water-exit nozzle. At the extreme right-hand side of the illustration Fig. 5 is schematically represented the flowpath of the water jet, with its violent changes of flow direction caused by these blows.

The indispensable feedback is not shown in Fig. 5 because there is a number of alternative possibilities. One of them is suggested in Fig. 6 on the previous page. Another is shown in Fig. 7 above.

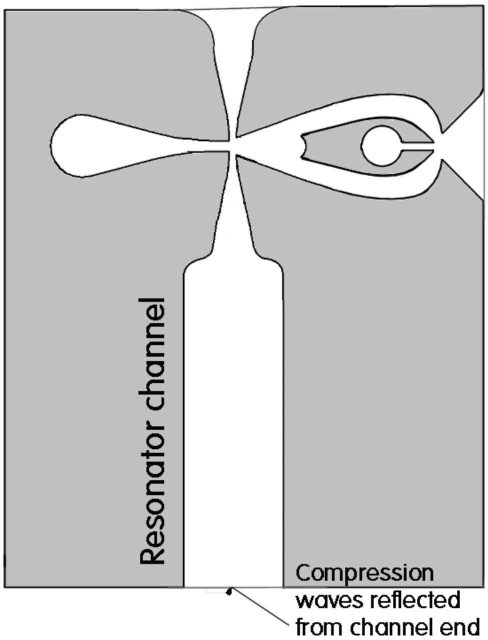


Fig. 7: Another alternative version of the atomiser, with feedback based on the alternating propagation of pressure and rarefaction waves in the resonator channel connected to one of the control nozzles. This is a relatively new feedback principle, described in detail in references [12, 13].

Structurally, the feedback shown in Fig. 6s is a simpler alternative than the two-loop version of the oscillator in Fig. 4 because there is only a single feedback loop channel. As was mentioned above, the Coanda effect of jet attachment to the attachment walls is based on the jet-pumping entrainment of outer fluid into the jet. On the wall side the entrainment is limited or stopped completely and this results on this side in lower pressure than on the other, outer side. This pressure difference, which bends the jet and inclines it towards the wall, is used in the configuration shown in Fig. 6 to generate the feedback control flow [11]. This flow alternates in its direction so that initially, after a direction change, it is weak. Gradually it increases in strength and the conditions may se adjusted to that the outflow from the ON control nozzle (the top one in Fig. 6) manages to switch the jet to the other, opposite attachment wall. The pressure difference between the two sides of the jet then changes sign. The flow in the feedback loop then stops and reverses its direction – finally also reaching the value at which it causes the jet to switch. These alternating phenomena lead to the desirable oscillation. General experience is, however, that this configuration of feedback is less reliable than the two-loop feedback, it is more difficult to adjust the conditions for the oscillation to start.

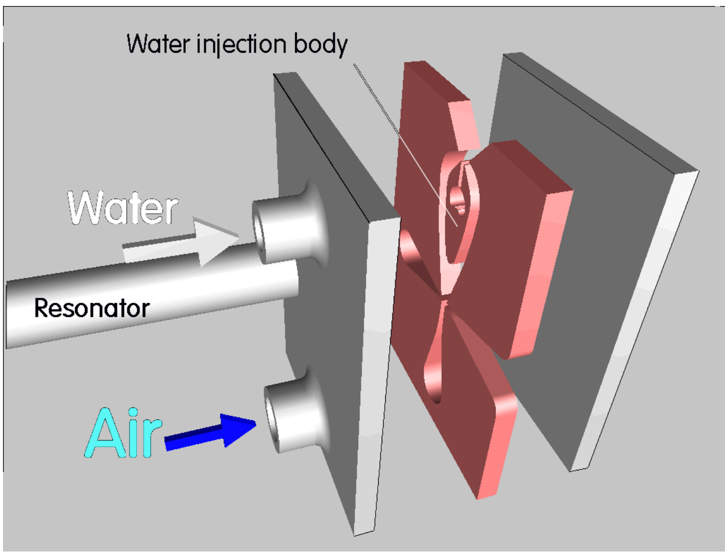


Fig. 8: Expanded view of the atomiser with feedback effect based on the propagation of compression and rarefaction waves in the resonator channel [12, 13] – the same as in Fig.7 which differs by the resonator formed by the metal tube fixed to the left-hand cover plate.

Another atomiser version is presented in Fig. 7. Basically the same principle, differing in geometric configuration of the resonator channel, is also presented in Fig. 8. Again, the atomiser consists of three plates (this is particularly well seen in Fig. 8, where the plates are shown expanded in space). Shown in Fig. 7 is only the middle plate of the three plates – the one with laser cut out cavities. Equally as in the cases presented in previous Figs. 4, 5, and 6, the gas is supplied into the atomiser cavities in the direction perpendicular to the drawing plane. This supply terminal is connected with the supply nozzle oriented from left to the right-hand side, into the interaction cavity between the two attachment walls. There are two control nozzles. The top control nozzle is open into atmosphere, while the second, bottom control nozzle is connected to the resonance channel. It is merely a cavity of constant rectangular cross section long its whole length. The opposite end of the resonator is also open into atmosphere. When the compressed air flow comes through the supply nozzle and forms the jet, the latter has to bend and attach to one of the two attachment walls. Since the configuration is not wholly symmetric – the hydraulic resistance of the control flow through the resonator is higher then on the opposite side where such resistance is absent, in this initial regime after the opening of the air flow the jet attaches to the bottom attachment wall. This is because - like all submerged jets - also the supply jet entrains air flow from its surrounding cavities. The entrainment on the bottom side is slightly more difficult and as a result, there is a lower pressure on the bottom side of the jet, which is bent by transversal pressure forces. The low pressure on the bottom side of the jet propagates through the resonance channel towards its free bottom end. When it reaches this end, a pressure wave is reflected from there and propagates upwards, towards the jet. The amplification effect of the fluidic amplifier is sensitive enough for this reflected pressure wave being capable – upon impact on the bottom side of the jet – of switching the jet. It stop moving to the bottom output terminal and flows into the upper one. However, after the switching the conditions become different. The open upper control nozzle is no more able to keep the jet deflected upwards. When the impact of the returned pressure wave from the resonant channel ceases to act, there is no more any force that would keep the jet bent upwards. It therefore returns to its bottom position. Once it is there, the low (sub-atmospheric) pressure on the bottom side of the jet (caused by its jet-pumping effect) becomes present and propagates downwards through the resonance channel. When it reaches this end, the reflected low-pressure (vacuum) wave is reflected – and this way the whole process as described above is repeated. This is a relatively new feedback mechanism, recently described in refs. [12] and [13]. The resonator channel need not be made by laser cutting in the main central plate of the atomiser as it is in Fig 7, but may have instead the form of a tube fixed to one of the cover plates. This version of the resonator is shown in Figs. 8 and 9.

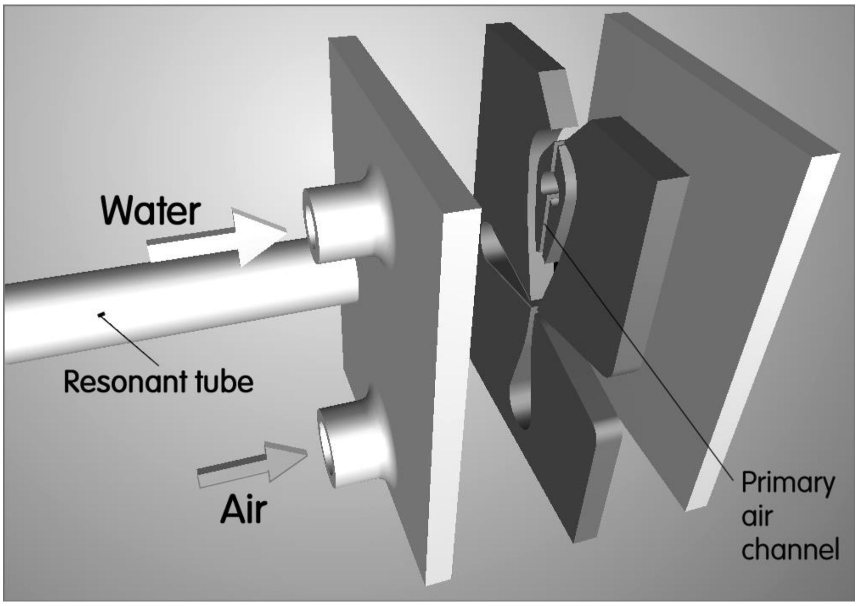


Fig. 9: Suggested version of the discussed new atomiser: by the simple mean of providing the primary air channel the version from previous Fig. 8 is converted into the atomiser of the effervescent type (c) from the list in Fig. 1.

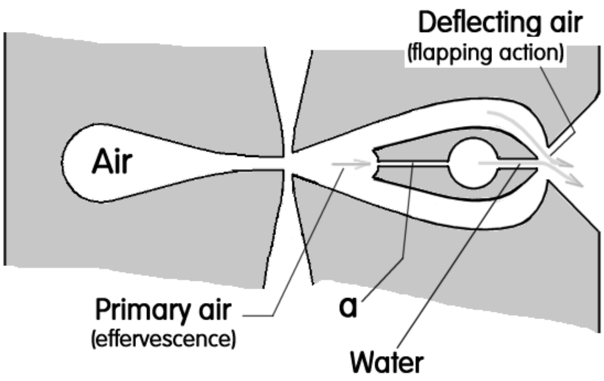


Fig. 10: The small adaptation – addition of the primary air channel "a" made in the water injection body – converts the discussed atomiser into the effervescent version (the air channel "a" has the same role as the internal mixing holes in Fig. 3.

There are other forms of feedback that may be used in the discussed atomiser. One of them that deserves being mentioned are the internal feedbacks. They are characterised by absence of feedback channels. Instead, the feedback signal is carried by vortical motions in the internal cavities. Because of the usually rather small size of the cavities and hence short signal travel time, this form of feedback us used in situation where there is a requirement if high oscillation frequency. An example of this internal feedback is discussed in ref. [14] – in a mixer in which it was not easy to identify the feedback existence - and another in [15], where there were special cavities made for the vortices.

Other alternatives of the atomiser design involve, for example, the versions shown in Figs. 9 and 10. The differ by the presence of the channel enabling the entry of air from the interaction cavity into water containing cavity inside the water-injection body. This additional channel admits some primary air flow so that – exactly as in Fig. 3 - instead of pure water leaves the water nozzle a two-phase mixture of water and air. Of course, the two fluids do not form any homogeneous mixture. There are small volumes of water alternating with also small volumes of air. Instantaneous velocities of air when leaving through this nozzle is much higher than the instantaneous local velocity if it is the water that is leaving. This velocity pulsation causes high shear stress on the liquid/air interface, leading to fragmentation of the small water volumes into even smaller droplets – and these are a short distance downstream exposed to the sudden large velocity direction variation, causing even more shear.

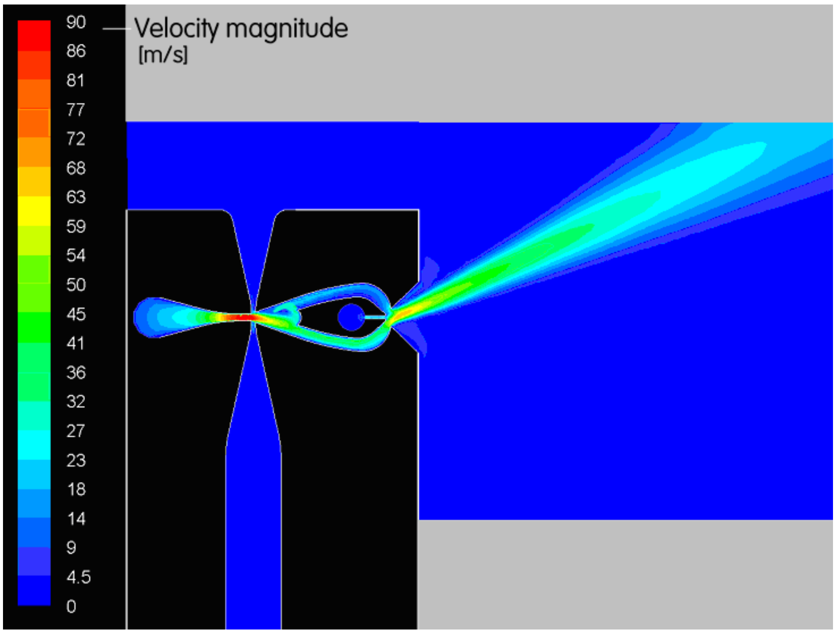


Fig. 11: A typical result of FLUENT numerical computation of the air flow (no water flow). Such solutions were made with different alternatives of atomiser details as a support for decisions concerning the design the atomiser mode. The colour coding used here indicates the absolute values of the local velocity.

4. Laboratory Model

The model made in the Institute of Thermomechanics was designed to process the water flow rate roughly ~ $3.6\ 10^{-6}\ m^3/s$ (an equivalent of 0.2 litres per minute). If possible, it was desirable to generate droplets of diameter ~ 0.1 mm = 100 μm.The design expected operation with the then new resonator type of the feedback as discussed in refs. [12] and [13]. Its cavities were to be made by laser cutting in two superposed plates of polymethylmetacrylate PMMA, each of them 2 mm thick. Apart from the higher precision of laser cutting (laser cut cavities tend to have slightly inclined walls when cut in a thicker material and this effect is suppressed if the thicker material is replaced by a stack of inner plates) it was considered an advantage to have the possibility of varying the nozzle aspect ration by using either one or two plates in the stack. In fact all experiments performed so far were made with only single central 2 mm plate. The laser-cut cavities were closed on both sides with thicker, 10 mm PMMA cover plates. The quite large thickness of the cover plates was considered necessary due to the low Young's modulus of PMMA material, because previous experience has shown that the internal fluid pressure in the cavities could slightly lift the cover plate between the clamping screws, enough for a non-negligible leakage.

The geometric shape of cavities was chosen by consideration of previous results obtained with the first author's earlier fluidic amplifiers. Because of the large number of variables and the non-linear character of their mutual dependence, it was not possible to apply any optimisation procedure to the geometry. It was decided to be satisfied with reasonably efficient and reliably oscillating configuration. Individual alternatives were tested by numerical flowfield computations – as shown in the example in Fig. 11.

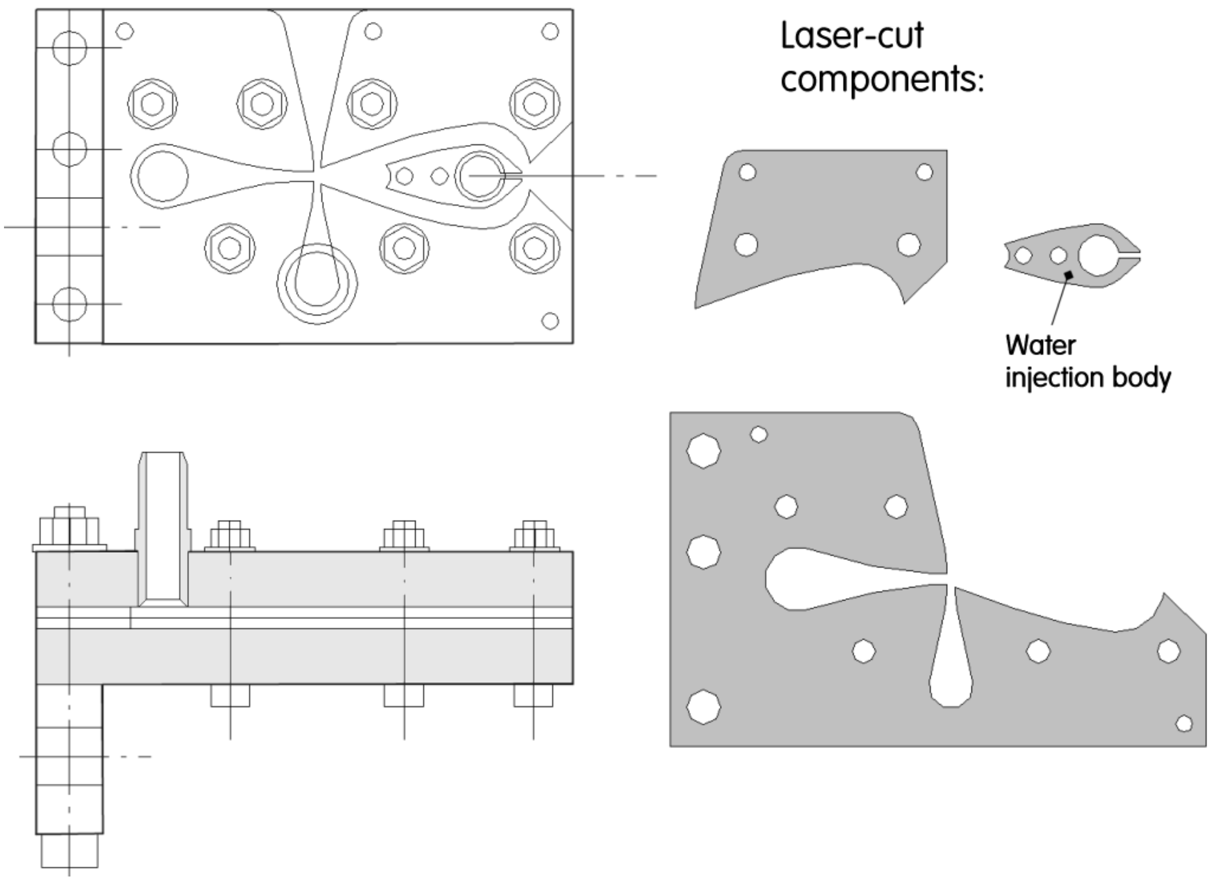


Fig. 12: Design of the laboratory model of the atomiser. Between the two 10 mm thick cover plates are two 2 mm thick identical central plates (only one of them was actually used in the experiments) with laser-cut cavities. Components of one of these plates are presented at right. The feedback was originally planned to use the principle shown above in Figs. 7 and 8 (at that time it was a new, promising solution).

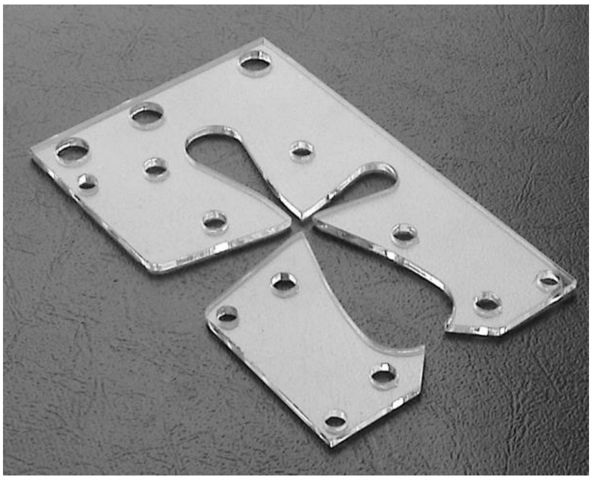


Fig. 13: Photograph of the two components of the central plate (i.e. without the water-injection body) laser cut in 2 mm thick PMMA.

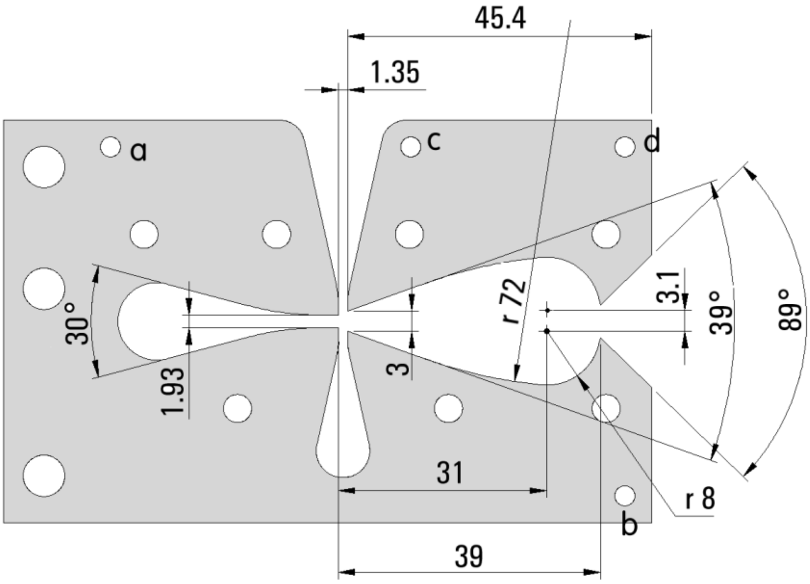


Fig. 14: Geometry and dimensioning of the plates of the main plate (the two components of which are shown in the photograph Fig. 13). Position of each component is secured by a pair positioning dowels: the larger component is fixed by dowels in the holes a and b. The other component is held in its proper position by dowels in the holes c and d.

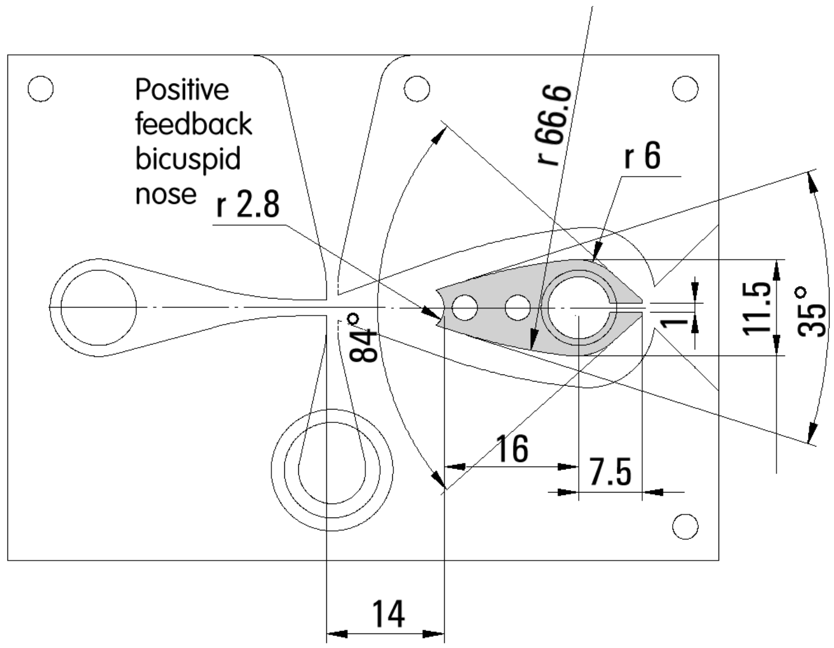


Fig. 15: Geometry, positioning and dimensions of the small water-injection body. Early tests were made with this body removed to obtain more experience with the consequences of configuration changes.

The design of the model is presented in Fig. 12. The dominant dimension is the width of the supply nozzle. Considering the manufacturing tolerances, instead of the nominal 2 mm width the dimension, the drawing sent to the suppliers, as shown in Fig. 14, shows the nozzle width to be 1.93 mm. Photograph of one of the two the most important central plates as it was received from the suppliers is presented in Fig. 13. A certain complication in manufacturing the central plates is the fact that the cutting operation produced three mutually separated components, as they are shown at the right-hand side of Fig. 12. The proper mutual positioning is secured by pairs of precision cylindrical steel dowels, the holes for which a, b, c and d are mentioned in the figure caption to Fig. 14.

A small component that also separates from the laser-cut plate is the water-injection body, Fig. 12. Details of its geometry are presented in Fig. 15. There are also two holes for the pair of positioning dowers – the place for which it was somewhat difficult to find in such a small component. Worth noting in this component is the bicuspid character of the upstream side of this body, with the half-moon shaped round cut-out between the cusps. This generates in the assembled atomiser a certain (weak) positive feedback effect already discussed above in the discussion of Fig. 4. Though not very prominent, this internal feedback loop is recognisable in the computed flowfield in Fig. 11.

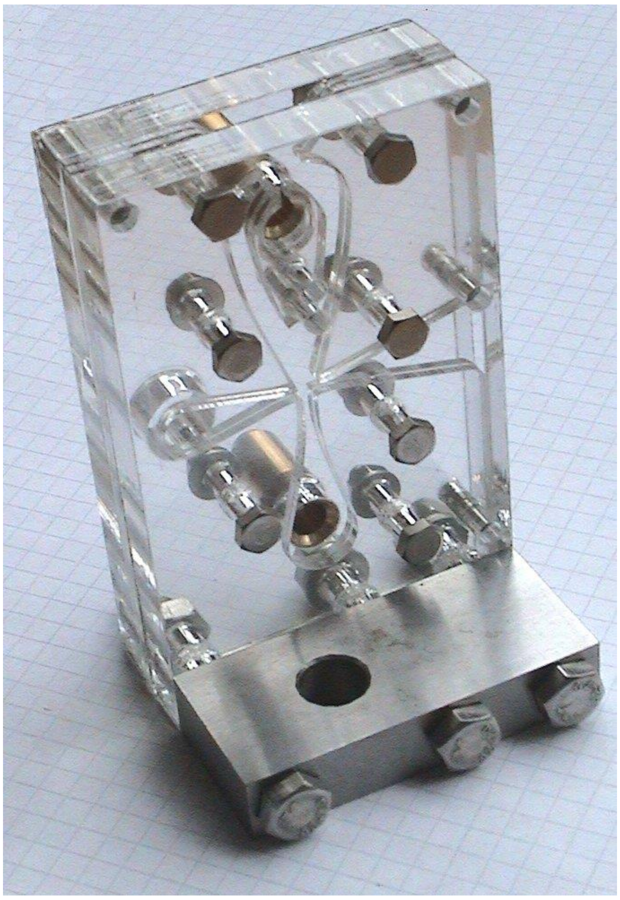


Fig. 16: Photograph of the atomiser in the preliminary assembly stage. The steel shin component at the bottom (also seen at the left-hand side of Fig. 12) is there to enable holding the atomiser inside the test chamber (enclosure in the chamber was needed to keep laboratory clean).

5. Preliminary Experiments

The primary aim of the experimentation was to obtain some understanding of the drop formation mechanism. A useful tool for this was the used high-speed video camera Vision Research Phantom v7.3, 14-bit monochrome model, set to resolution 800 x 600 pixels. The key component was a long-distance macro-lens Machine Vision NAVITAR 12X that made possible taking pictures of the small objects from a safe distance as far as 100 mm away from the front lens (through walls of protective glass vessel). Essential for the high-speed recording was high intensity illumination of the very small target scene. The light source used was a 40 W input power white colour LED system, producing total luminous flux 1 800 lm, concentrated by a narrow-beam optics. Under these conditions, the camera could be run at the speed 40 000 frames per second, i.e. at 25 μs interval between the images.

Initial recording of water alone. Velocity by tracing a particular droplet. of submillimetre size, coalescence into larger drops. velocity, flow rate

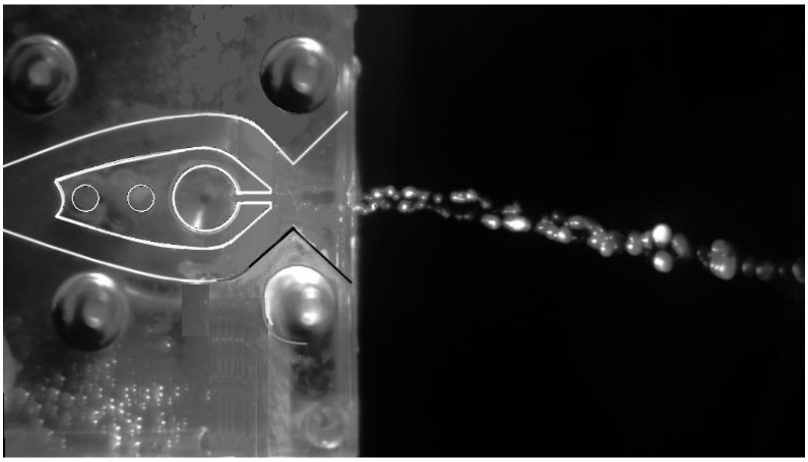


Fig. 17: A frame from the high-speed camera record obtained in preliminary tests of the atomiser – with water flow alone. Note the large size of the drops produced in the simplest configuration corresponding to the case (a) in Fig. 1, Tracing an individual droplet in camera frames made possible establishing the magnitude of the water flow velocity (in parallel with an independent measurement of collecting the water drops for a timed period).

6. Water Injection Body Removed

The aim: generating a complex flow with violent changes of velocity direction and magnitude.

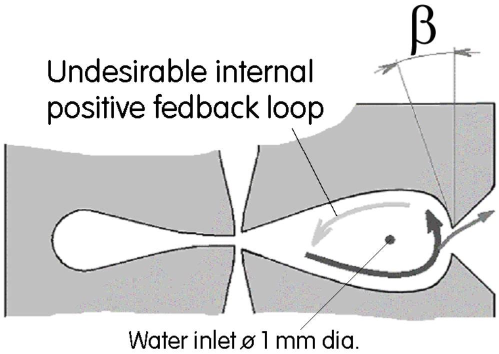


Fig. 18: Explanation of the reason for failure of the earliest tests with removed water-injection body. Water was injected through the 1 mm hole in the bottom cover plate. The atomiser refused to oscillate because the strong positive vortical feedback indicated by the arrows kept the air jet permanently deflected at one of the attachment walls.

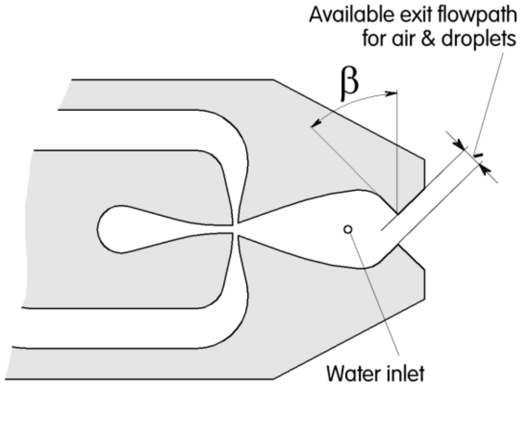


Fig. 19: Simple change of the atomiser exit geometry eliminated the unwanted positive feedback and started the oscillation. The exit wall angle β was increased (compare it with with Fig. 18) and the air/water mixture flow was given an opportunity to leave through the wide, properly inclined exit path.

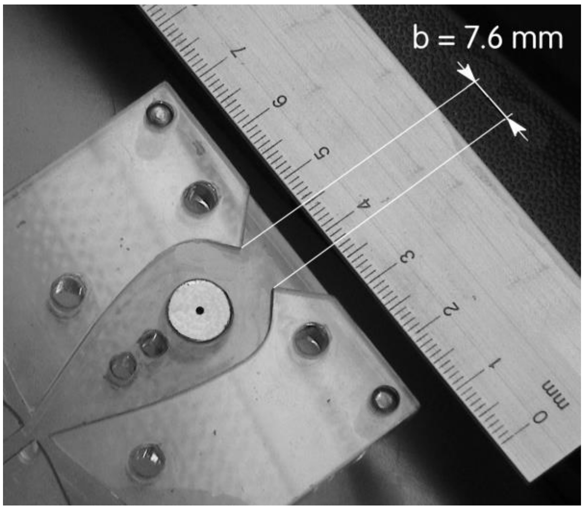


Fig. 20: Photograph of the business end of the atomiser with the water-injector body removed. This image was used to establish the conversion ratio between the size of photographed objects in pixels and in millimetres.

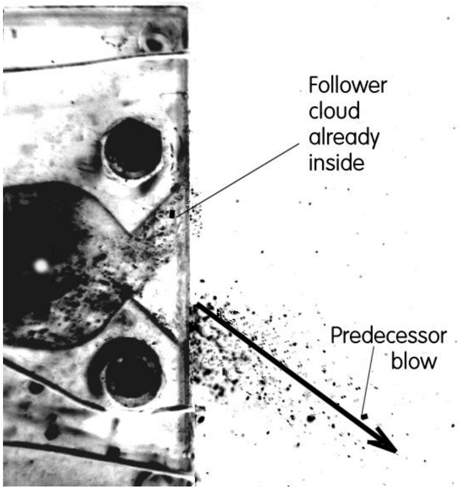


Fig. 21: Negative photograph of the atomiser without the water-injector body in operation. Inclined airflow blows leaving the atomiser cavities alternate by almost 90 deg in their motion direction when leaving the aerator: the bottom cloud of droplets has already left the atomiser body, the top blow is still within the exit. Presentation in photograph negatives was found to makes it easier to see the individual small droplets (especially with ink-jet printed pictures).

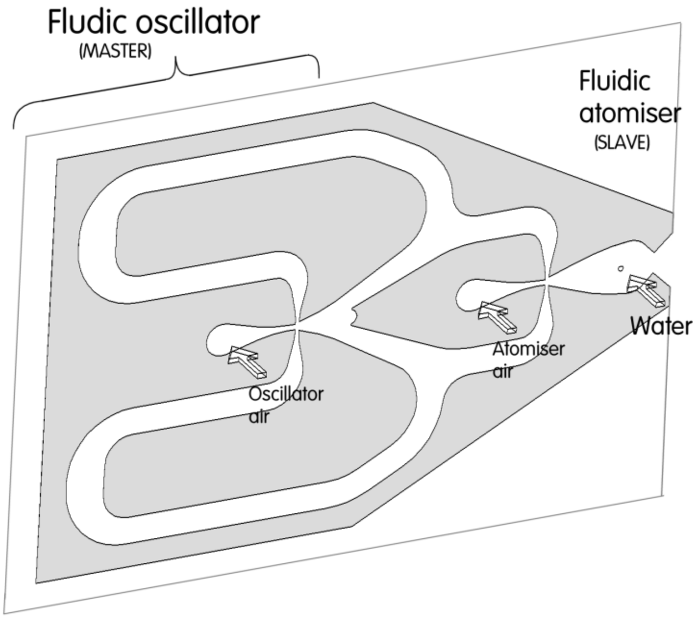


Fig. 22: Even though the developed atomiser was demonstrated to be capable of operating in the self-excite oscillation regime, recurrent problems with the feedback instability have led to simplifying the adjustments by using the two-stage layout shown here in perspective view. The oscillator and atomiser actuator stages were individually adjustable. This illustration shows a possible layout with stages manufactured at once in the same manufacturing operation. In the discussed tests, however, the stages were separate.

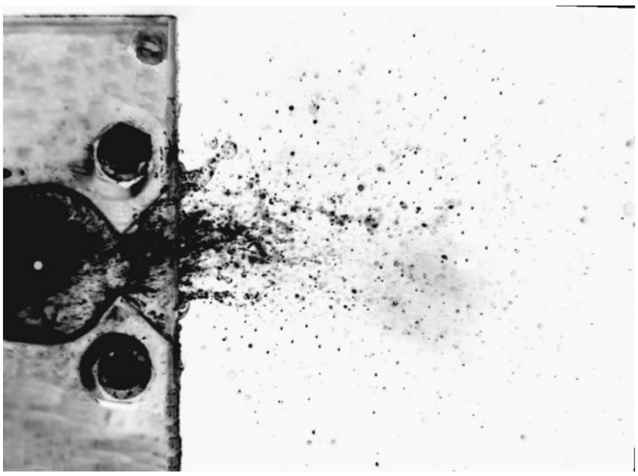


Fig. 23: Negative grayshade colour photograph of the spray formed by the atomiser with removed water-injection body. In an attempt to generate the full ~ 90 deg fan of droplets, the water flow rate was in this case increased several times beyond the nominal design conditions.

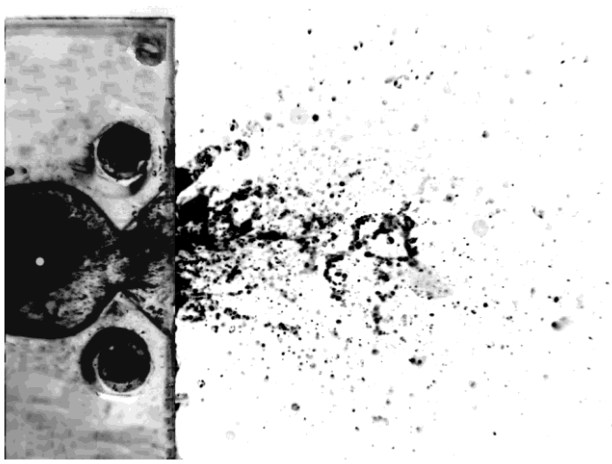


Fig. 24: Negative colour photograph of the spray (a frame from high-speed camera) the spray formed without water-injection body and water flow rate increased above the level of the one in Fig. 23. The air flow was also larger but its increase could not keep pace – and this resulted in incomplete fragmentation in the atomiser exit. The visible water ligaments are decomposed further downstream by the Plateau-Rayleigh mechanism, nevertheless the final droplet size is unacceptably high.

Fig. 25: Photograph (again in the inverse grayscale) of the spray generated with the water-injection body again in its place. Velocities are higher, kinetic energy is not lost inside the interaction cavity with the complex internal flow. High speed: recognisable from smearing the droplet pictures despite the vely short exposure time 39 μs

The principle of the droplet size measurement by the Spraytec instrument is presented in Fig. 25. The light-beam generating part of the instrument is shown schematically at the left. Light from the laser is expanded by the collimating optics and produces wider parallel beam passing rougly ~ 45 mm downstream from the exit of the atomiser. This light is scattered by droplets that happen to be witjin this beam. The scattered light is focused by focusing lens in a Fourier arrangement and the diffraction angle – inversely proportional to the droplet size - is evaluated by the detector.

The space between the transmitter and receiver (in particular the walls of the protective containment vessle inside which is the sprqay generated) may possess various optical qualites and also the length of the optical path may vary. This is compensated for by means of auxiliary unscattered light which passes through the pinhole at the centre of the detector array and is measured by the beam power detector.

The detector array **5** is made up of over 30 individual detectors, each of which collects the light scattered by a particular range of angles. There is a data channel for each of these individual detectors. Diffraction is influenced by optical properties of the water and of the gas in the bubbles. The user has to input into the instrument the data on refractive index and density.

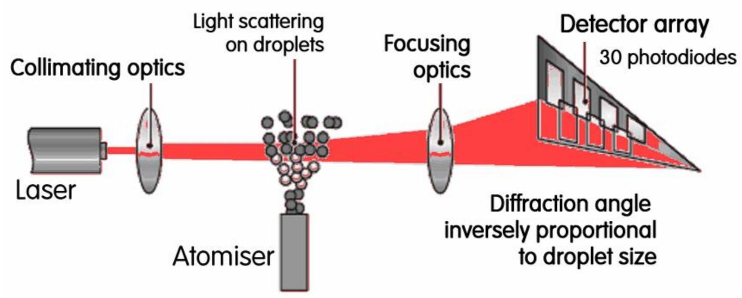


Fig. 26: The principle of the instrument used for optical measurement of the critical performance factor – the smallness of the final droplets. The collimated parallel laser light beam was positioned ~ 45 mm downstream from the atomiser exit.

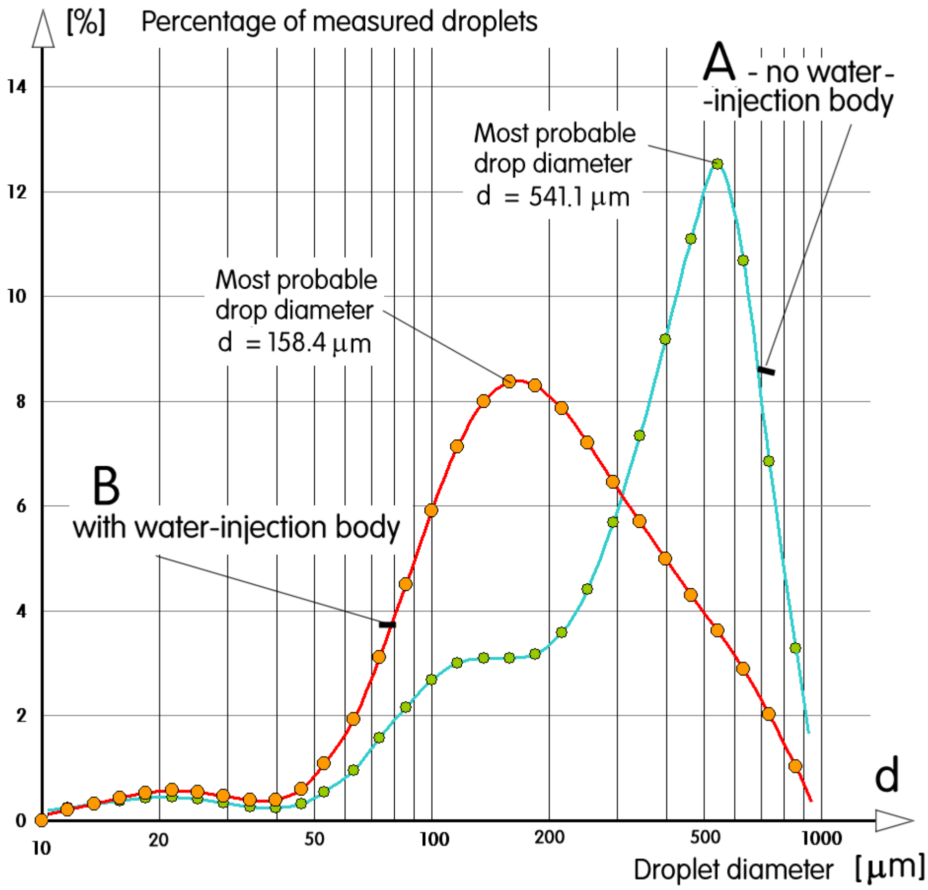


Fig. 27: Example of measured size spectra of generated droplets. The target was to obtain most probable diameter ~ 100 μm and the results obtained in the configuration with the water-injection body show that achieving it by further development is reasonably achievable.

Acknowledgements

Authors' research was supported by grant 13-2304S obtained from GAČR. They were also recipients of institutional support RVO: 61388998. Gratefully acknowledged is the help of Dr. Jiří Šonský who kindly made available his high-speed camera and software for image processing. In their experiments authors were helped by Doc. M. Jilek.